INL/CON-24-78465-Revision-1

Pre-Transient Characterization of Historic EBR-II Pins for Transient Testing

June 2024

Changing the World's Energy Future

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Pre-Transient Characterization of Historic EBR-II Pins for Transient Testing

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Performance Considerations for Metallic Fuel Pins in SFRs

Fuel Axial Elongation

- Fuel column stretching/lengthening
  - irradiation-induced swelling
  - thermal expansion
  - mechanical stress

Fuel Constituent Redistribution

- Thermal and chemical gradients drive element migration
- Altered compositions impact present phases, porosity, and thermo-mechanical properties within the region

FCMI

- Fuel expansion due to FP accumulation and irradiation damage
- Closure of fuel-clad gap results in mechanical stress applied to cladding

FCCI

- Chemical interdiffusion between cladding and fuel constituents
- FCCI compromises cladding integrity and causes low-temperature melting eutectic

Fission Gas Release

- Fission gases accumulate along grain boundaries and voids within the fuel matrix
- Gases released due to mechanical stress and thermal diffusion

Fuel-Coolant Compatibility

Fuel and coolant must maintain adequate compatibility to avoid pin corrosion, aggravation of breached pins, and propagation of failures.

Possible Transient Scenarios in SFRs

Transient Overpower (TOP)

Rapid Reactivity Insertion

- Unplanned Control Rod Ejection
- Failure of Control Rod Insertion

Loss of Flow (LOF)

Disruption in Core Cooling

- Partial Reduction in Coolant Flow
- Complete Cessation of Coolant Flow

Historic Transient Testing of Metallic Fuels

Transient Overpower (TOP)

Overpower Transient-1 (OPT-1) at EBR-II

- Slow ramp test to 1.32 x nominal power
- 19 Irradiated EBR-II Pins (15 U-xPu-xZr, 4 U-Zr)
    - Burnup Range: 5.5-12.7 at.%
- No pin breach
- No additional contribution to FCMI, FCCI, constituent redistribution, axial deformation

Metallic (M-Series) Tests at TREAT

- 9 U-Fs pins, 5 U-19Pu-10Zr pins, 1 U-10Zr
    - Fresh-9.8 at.% burnup
- 3.2-4.8 x nominal power, 8-s period
- Greater axial elongation in U-Fs pins
    - Due to higher operating temp. and decreased retained fission gas
- Pin failure attributed to low-melting eutectic
- Internal pin pressure also aggravated fuel response, resulting in expulsion of melted fuel (M5-M7)
- M8 test was planned prior to TREAT shutdown

Loss of Flow (LOF)

Shutdown Heat Removal Tests (SHRT) at EBR-II

- Conducted on U-Fs EBR-II Fuel Pins
- Protected and Unprotected LOFs
    - Effective plant protection system
    - Shutdown via inherent safety mechanisms
- Core temperatures stayed within operational limits

Fuel Behavior Test Apparatus (FBTA) Series

- 8 U-xPu-10Zr, 20 U-10Zr Pins (3-10 at.%)
- Higher BU pins have lower thresholds for eutectic
- Found time- and temp.- relationship to eutectic

Whole Pin Furnace (WPF) Tests

- 6 U-19Pu-10Zr, 1 U-10Zr Pins (2.2-13.3 at. %)
- No breach, melting, or FCCI increase in UN-1
- Long temperature holds (1-2 hours)
    - Demonstrated large margin to failure
- Low BU failed due to low-melting eutectic
- High BU failed due to creep rupture in plenum

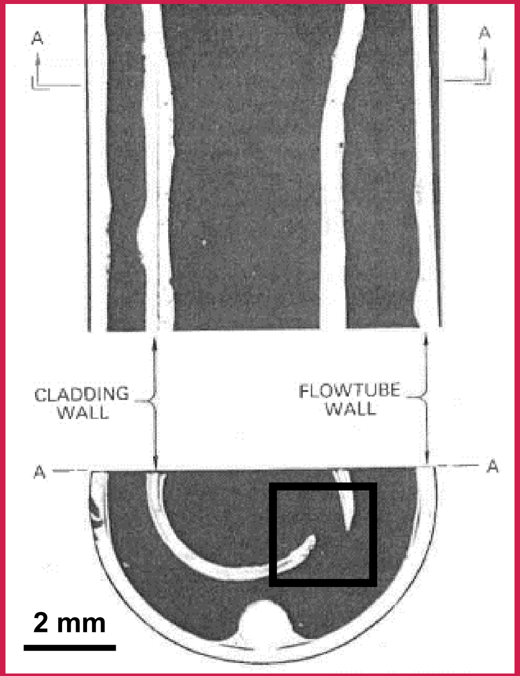
Failure Mechanisms During Transient

Low-Melting Eutectic Formation

0.8 at. %
U-19Pu-10Zr
D9 Clad

Bauer et al. Nuclear Fuel Cycles, 1990

Thermal Creep Rupture



7.9 at. %
U-5Fs
316 SS Clad

Bauer et al. Technical Report, 1989

Pin Burnup

Margin to Pin Failure Dependent on Many Variables

- Fuel Pin Geometry
  - Smear Density
  - Plenum to Fuel Volume Ratio
  - Cladding Diameter and Thickness
- Fuel Composition
  - Pu, Zr, Transuranic Elements, Rare Earth Elements
- Irradiation Conditions
  - Peak Temperature
  - Burnup
  - Power
  - Ramp Rate
  - Fast Fluence

The interconnected effects of these variables on fuel pin behavior cannot be fully understood from limited historic transient testing alone

Addressing Gaps in Transient Behavior of Metallic Fuel

- Establishing a transient testing capability that can test irradiated U-Pu-Zr and U-Zr fuel pins under representative accident conditions utilizing a comprehensive characterization suite and modern analysis techniques
- Perform TOP and LOF tests to extract data showing the effects of transient conditions on metallic fuel behavior, informing both models and safety limits
  - THOR-M-TOP
  - THOR-M-LOF

IV. Comparisons drawn between pre- and post-transient results and historical irradiation/test database

I. Pre-transient non-destructive and destructive examination using test and sibling pins

II. Full pin TOP and LOF irradiations in TREAT Facility

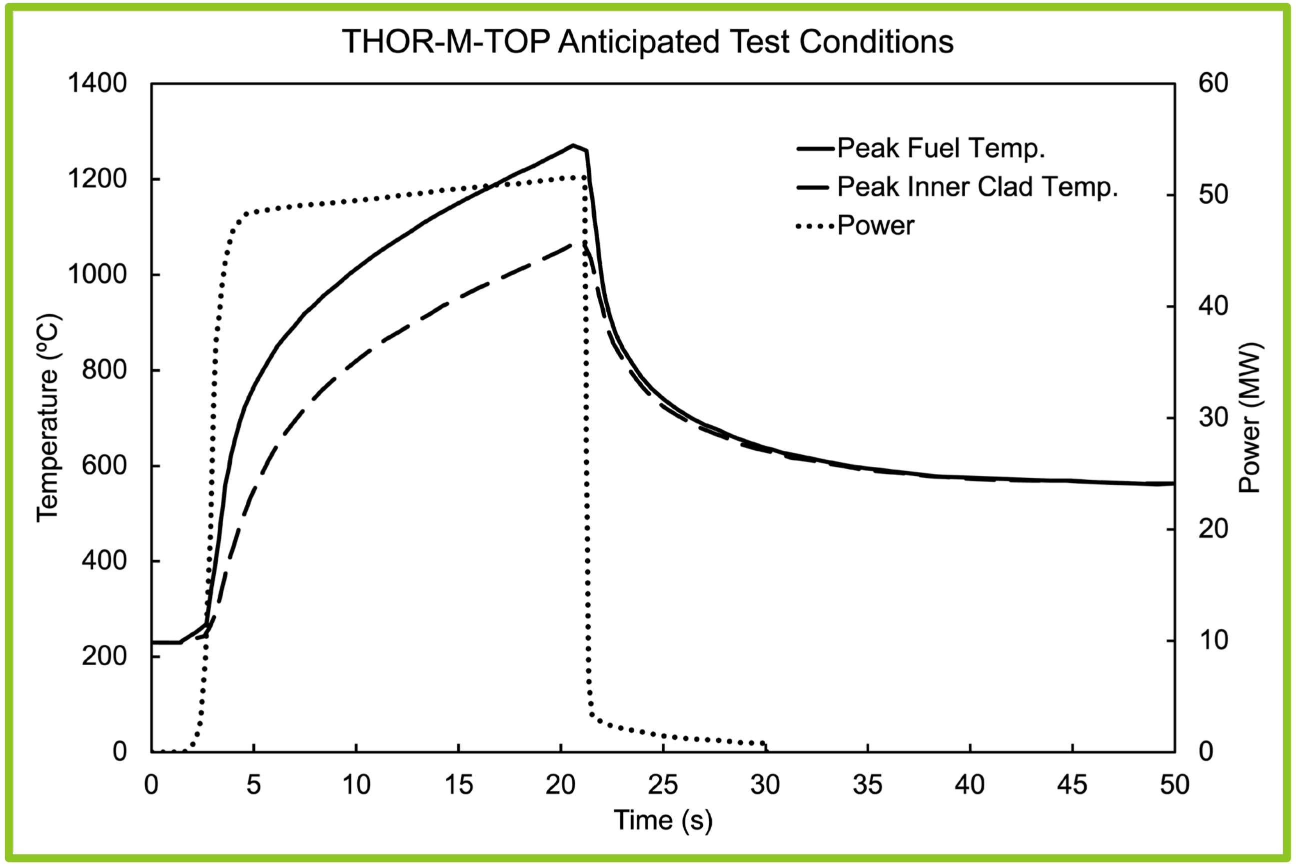
III. Post-transient non-destructive and destructive examination on test pins

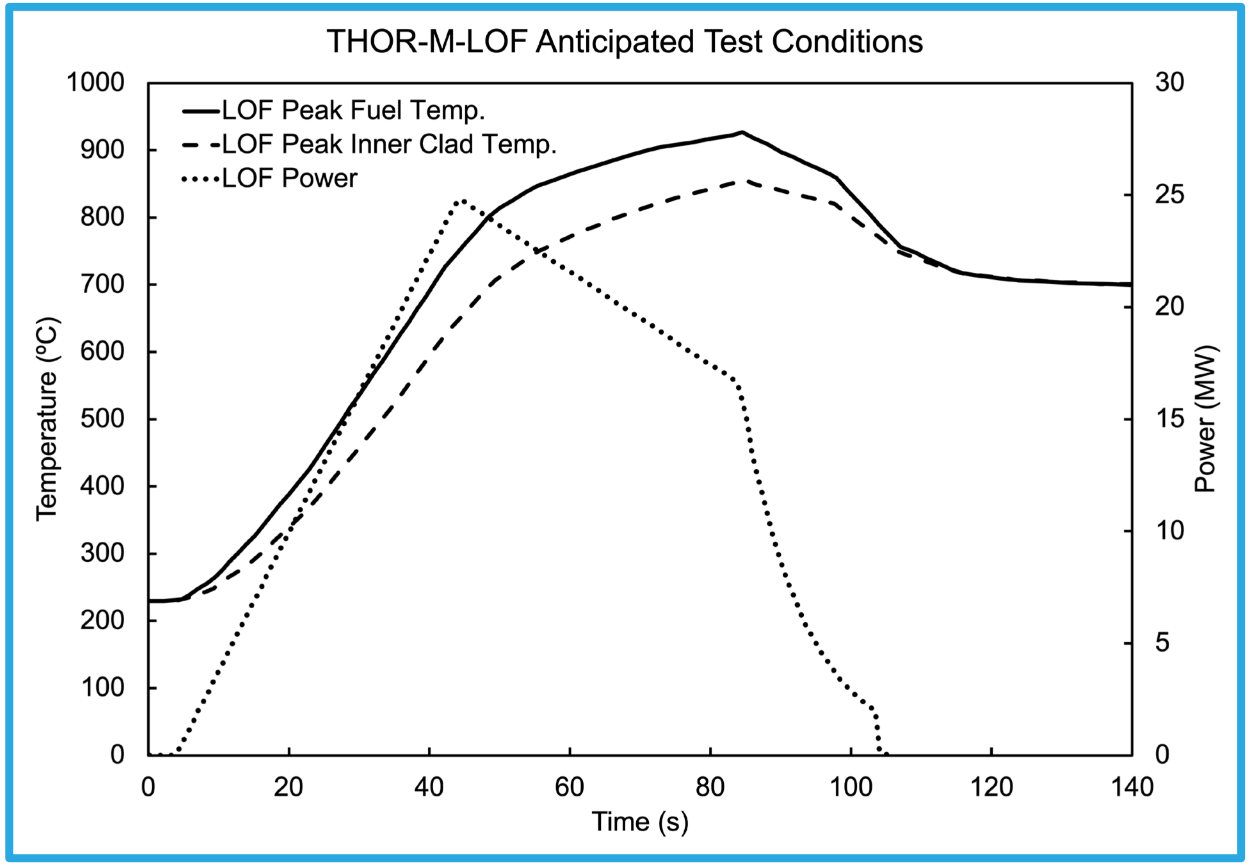
Test and Sibling Pin Specifics for M-TOP and M-LOF

	THOR-M-TOP		THOR-M-LOF	
Experiment and Pin ID	X441A-DP40	X441A-DP36	X430A-T679	X430A-T681
Composition	U-19Pu-10Zr	U-19Pu-10Zr	U-10Zr	U-10Zr
Nominal Fuel Length (cm)	34.3	34.3	34.3	34.3
Nominal Element Length (cm)	74.9	74.9	74.9	74.9
Fuel Diameter (mm)	4.39	4.39	5.71	5.71
Cladding Material	HT-9	HT-9	HT-9	HT-9
Cladding Outer Diameter (mm)	5.84	5.84	7.37	7.37
Cladding Thickness (mm)	0.38	0.38	0.406	0.406
Plenum to Fuel Volume Ratio	1.1	1.1	1.4	1.4
Smear Density	75%	75%	75%	75%
Calculated Peak Burnup (at.%)	11.1	11.6	7.4	7.3
Experiment Peak Power (kW/m)	45.9	45.9	49.2	49.2
Experiment Peak Clad. Temp (°C)	600	600	540	540
Experiment Fast Fluence ($\times 10^{22}$ n/cm^2)	10.1	10.1	20.6	20.6
Heat Sink Material	Ti-64	Ti-64	Ti-64	Ti-64

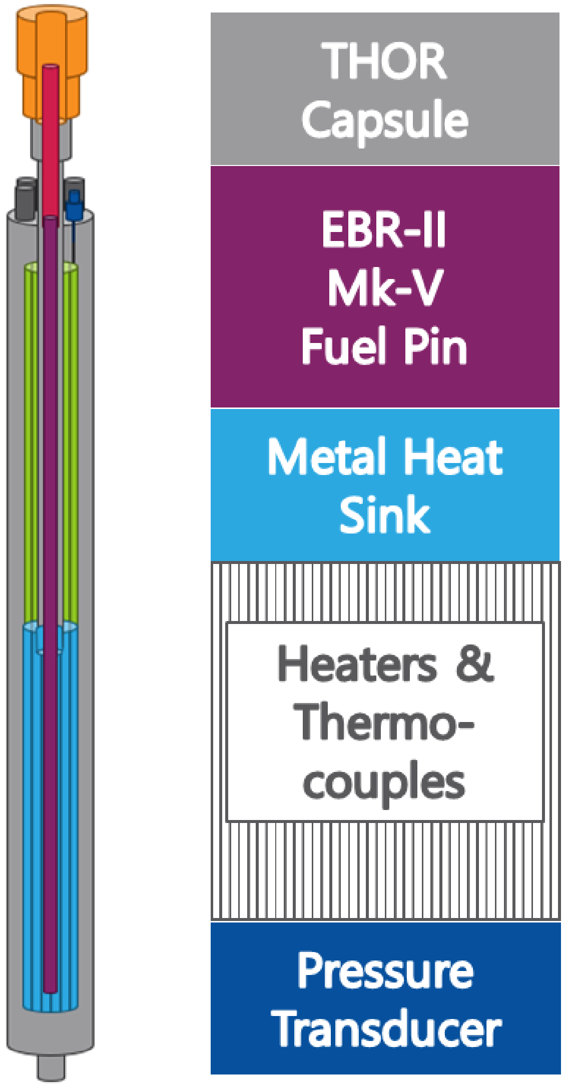
Planned Irradiation Conditions

- Each test pin (DP-40 for M-TOP, T-679 for M-LOF) will be loaded into a static sodium test capsule and subjected to a shaped transient in the TREAT facility





In-Situ Monitoring Provides Insight into Fuel Pin Response



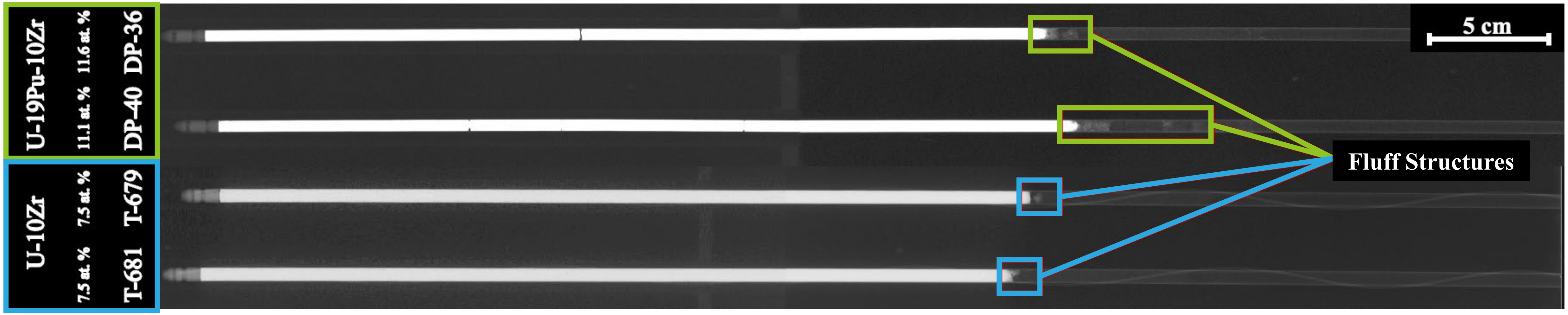
- Transient Heatsink Overpower Response Capsule
  - Houses full size EBR-II fuel pin
  - Static sodium environment
  - Tight thermal coupling between pin, sodium bond, and heat sink
- Instrumentation within THOR
  - Thermocouples
  - Linear Variable Differential Transformer
  - Acoustic Emission Sensor
- Instrumentation within TREAT
  - Fuel Motion Monitoring System (Hodoscope)

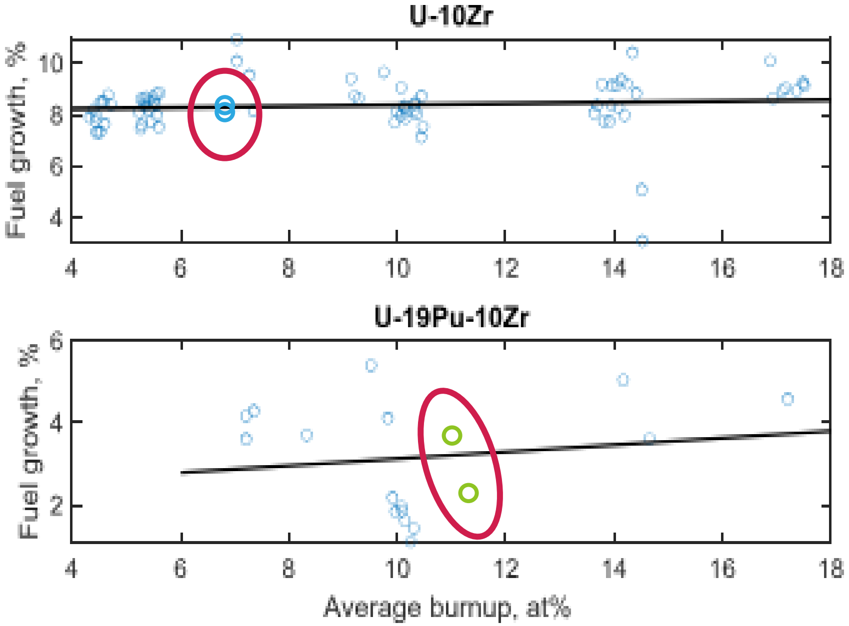
Planned Pre-Transient Characterization

	Examination	THOR-M-TOP		THOR-M-LOF	
		X441A-DP40	X441A-DP36	X430A-T679	X430A-T681
Non-Destructive	Visual (VEM)	C	C	C	C
	Neutron Radiography (NR)	C	C	C	C
	Element Contact Profilometry (ECP)	C	C	C	C
	Precise Gamma Scan (PGS)	C	C	C	C
Destructive	Fission Gas Assay, Sample, and Recharge (GASR)	-	C	-	C
	Optical Microscopy (OM)	-	C	-	P
	Scanning Electron Microscopy (SEM)	-	P	-	P
	Electron Probe Microanalysis (EPMA)	-	P	-	P
	Laser Flash Analysis (LFA)	-	P	-	P
	Burnup (BU) Analysis	-	P	-	P

C = Completed, P = Planned

Baseline Axial Elongation using Neutron Radiography

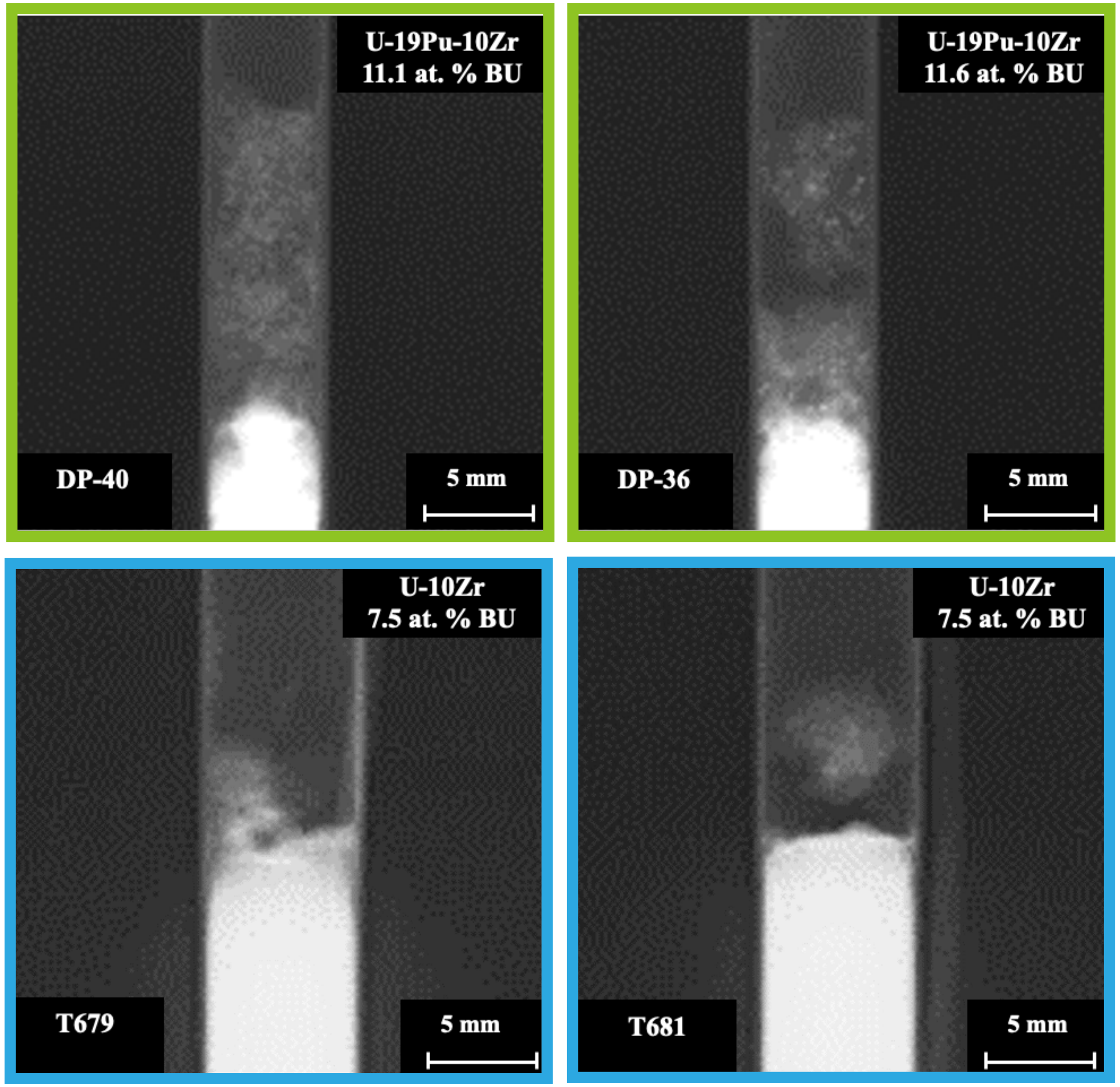




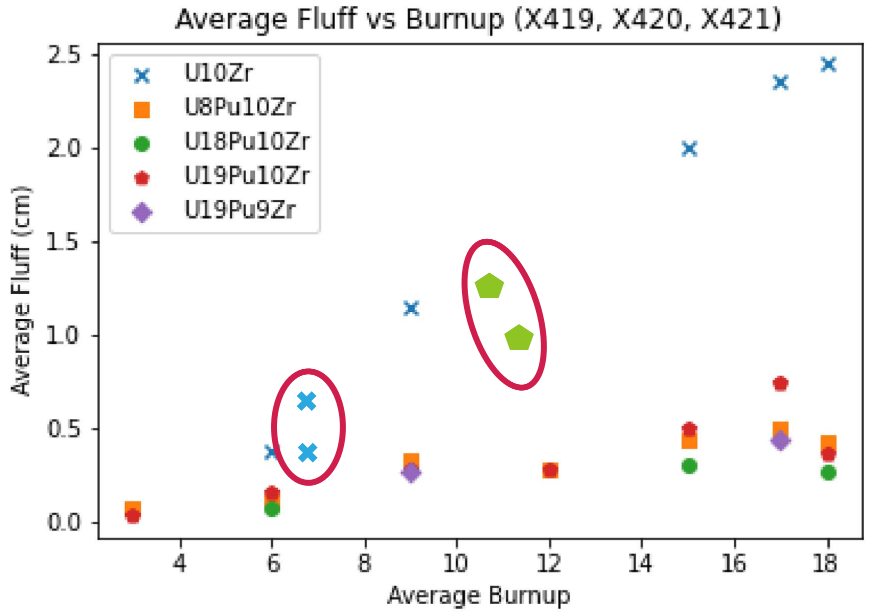
Gribok et. al., Journal of Nuclear Materials, 2021

Test	M-TOP		M-LOF	
Fuel Pin ID	DP-40	DP-36	T-679	T-681
Peak BU (at. %)	11.1	11.6	7.4	7.3
Axial Growth (%)	3.6	2.1	8.2	8.0

Fluff Structures of THOR-M-TOP and THOR-M-LOF Pins

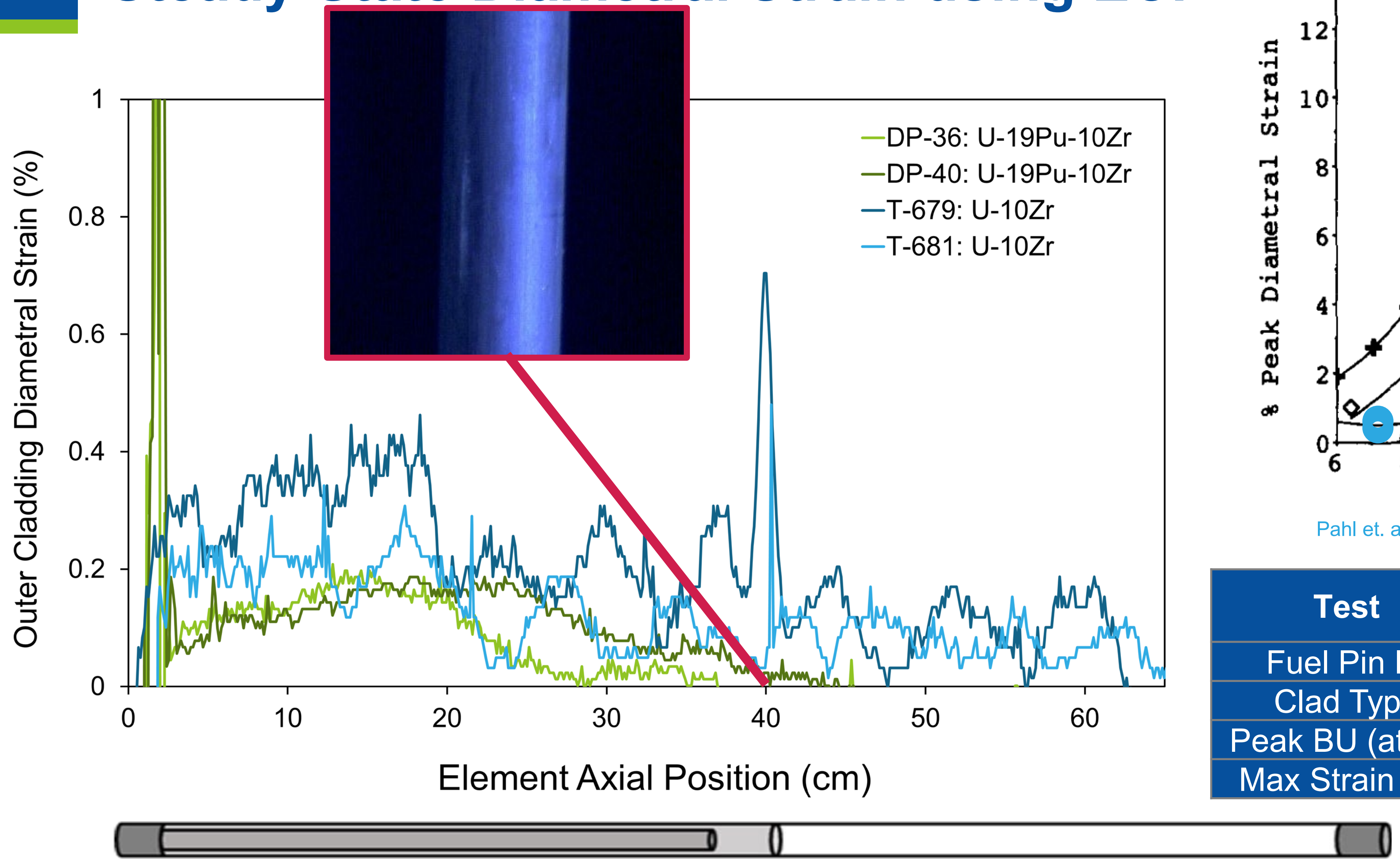


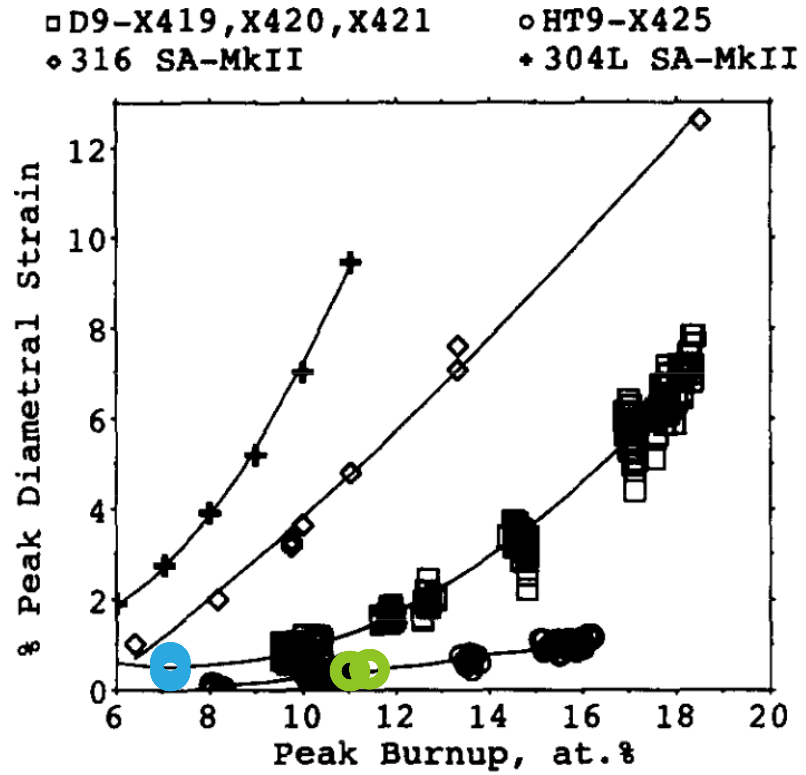
- Porous, cloudy region at the top of fuel column
  - Na bond extrusion to plenum
  - Fission product solubility in Na
  - Fuel-Na interaction



Fay et. al., Journal of Nuclear Materials, 2022

Steady-State Diametral Strain using ECP

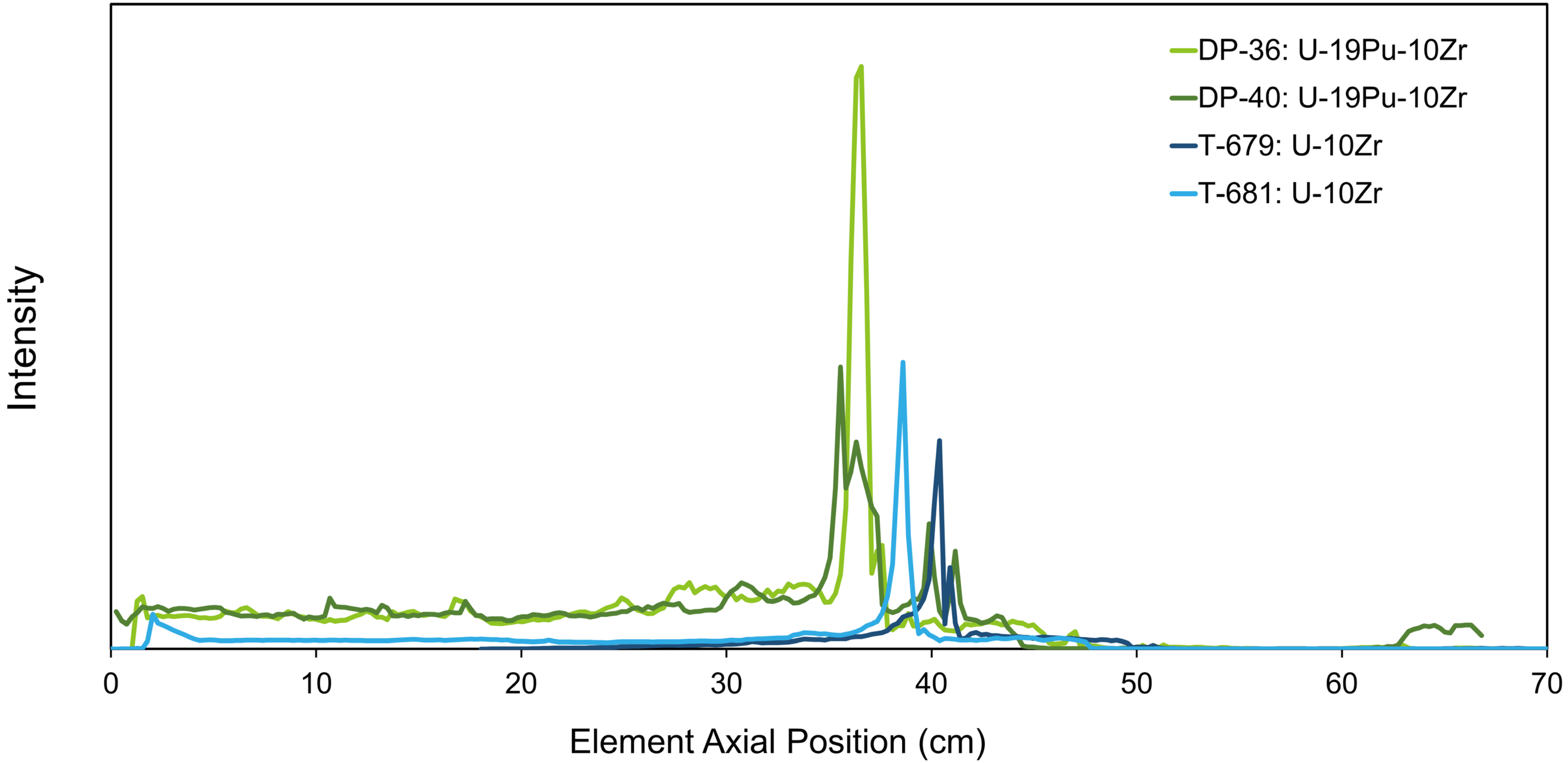




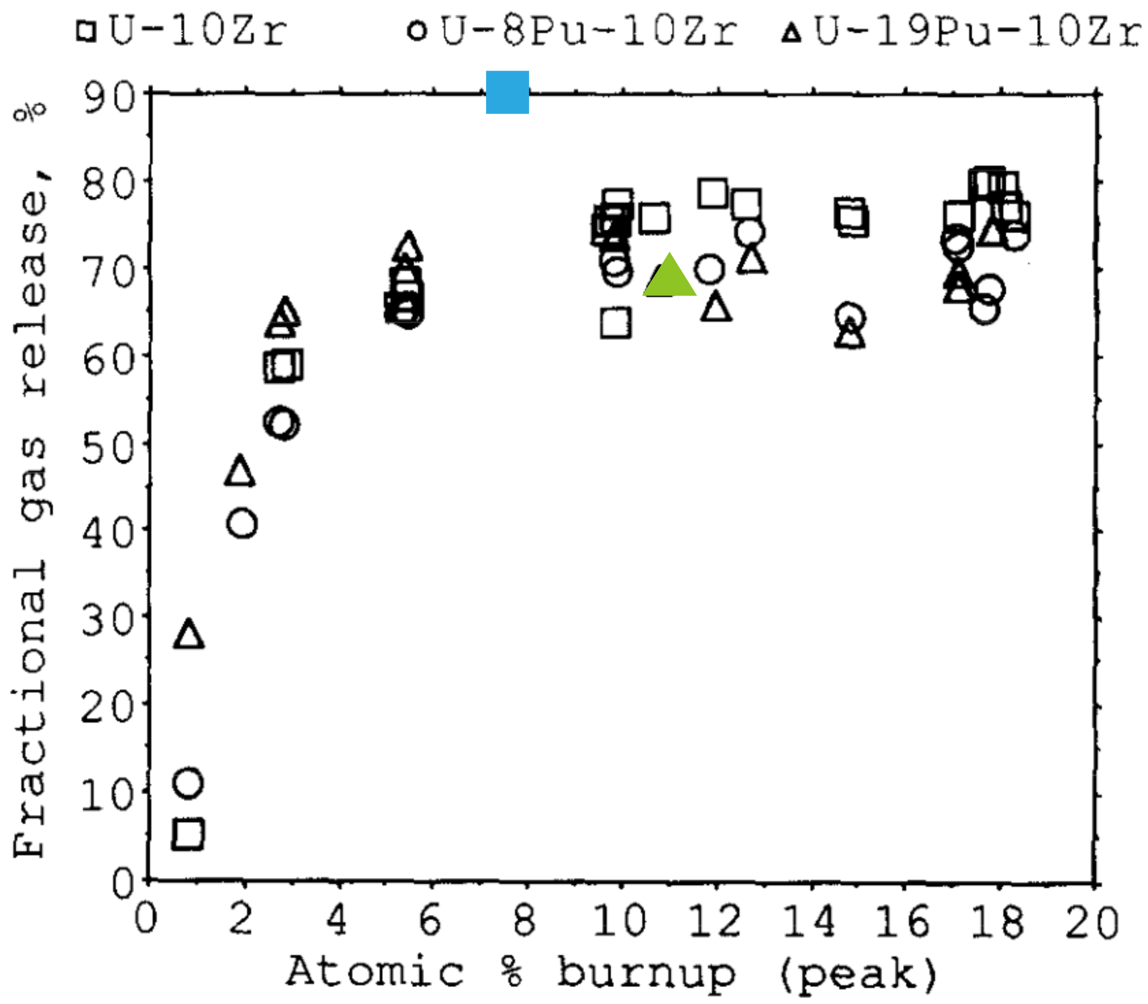
Pahl et. al., Journal of Nuclear Materials, 1992

Test	M-TOP		M-LOF	
Fuel Pin ID	DP-40	DP-36	T-679	T-681
Clad Type	HT9	HT9	HT9	HT9
Peak BU (at. %)	11.1	11.6	7.4	7.3
Max Strain (%)	0.34	0.30	0.68	0.34

Steady-State ^{137}Cs Distribution using PGS



Steady State Fractional Gas Release using GASR Analysis

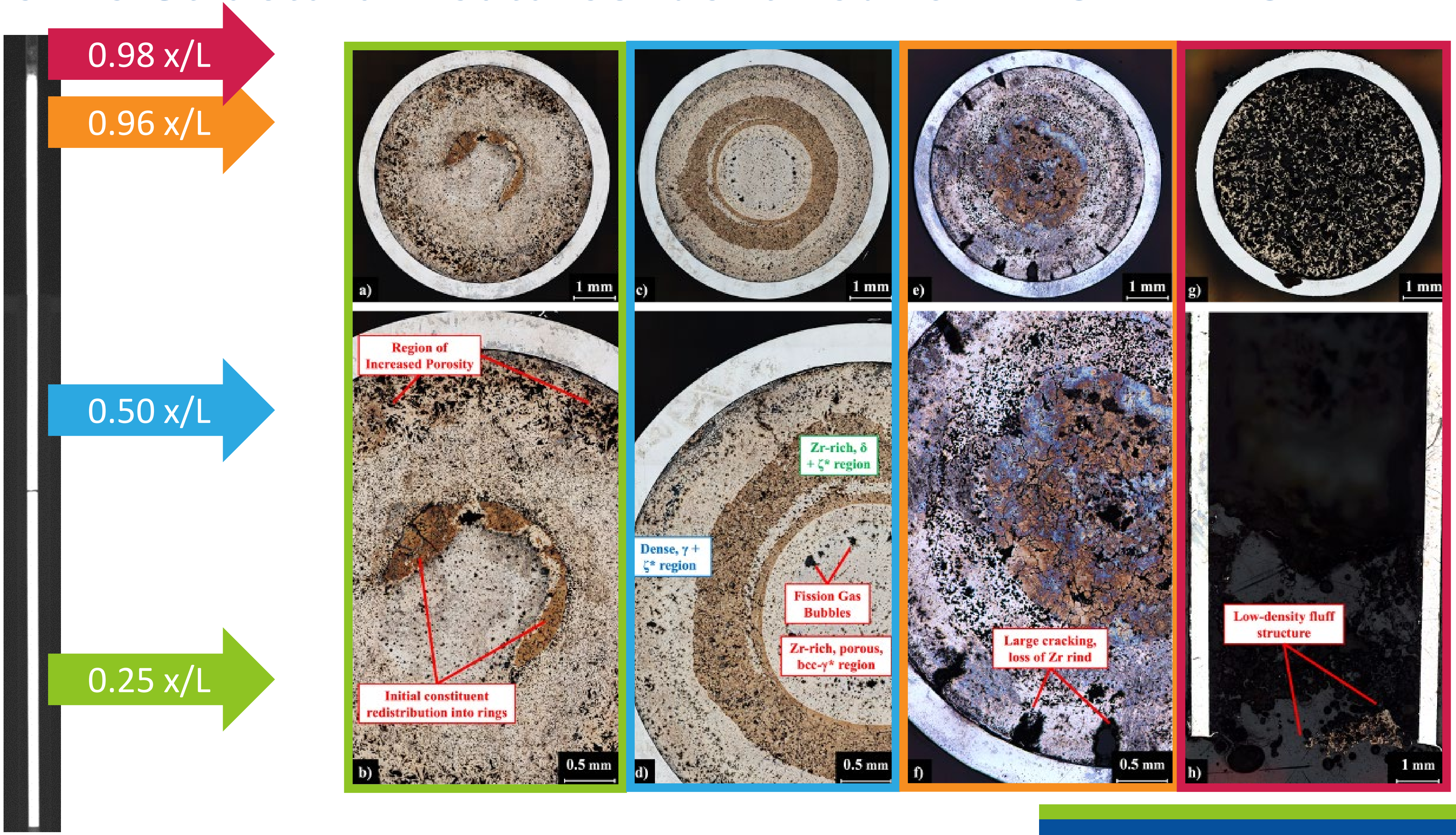


Pahl et. al., Journal of Nuclear Materials, 1992

- Plenum Pressure and Volume Measurements
- Mass Spectrometry on Sampled Fission Gas
- Total Kr + Xe gas production calculated empirically

Test	M-TOP	M-LOF
Fuel Pin ID	DP-36	T-681
Composition	U-19Pu-10Zr	U-10Zr
Peak Burnup (at. %)	11.6	7.3
Kr+Xe Gas Release (%)	68%	92%

Baseline Structural Features Identified for THOR-M-TOP



11.6 at.% peak burnup U-19Pu-10Zr

Work Still to be Conducted and Analyzed

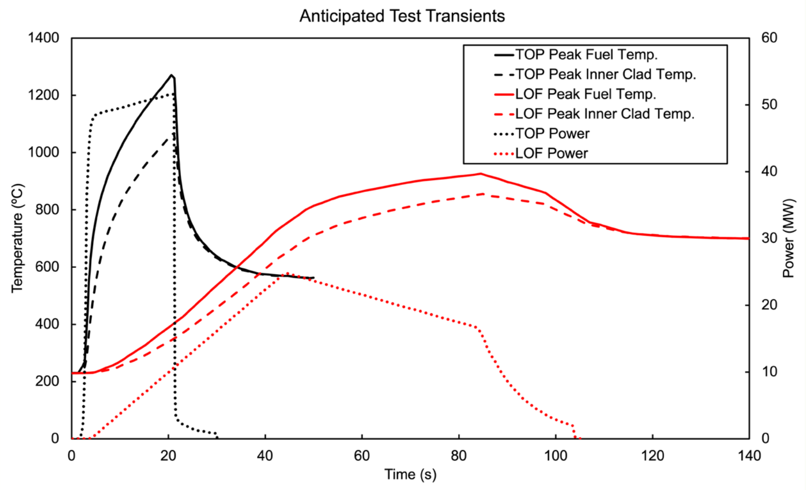
IV. Comparisons drawn between pre- and post-transient results and historical irradiation/test database

I. Pre-transient ND/DE

Both Sibling Pins (DP-36, T-681)
- SEM
- EPMA
- LFA
- Burnup Analysis

THOR-M-LOF Pin T-681:
- Sectioning
- Optical Microscopy

II. TOP and LOF transient irradiations in TREAT



III. Post-transient NDE/DE

Both Test Pins (DP-40, T-679)
- Visual Examination
- Neutron Radiography
- Element Contact Profilometry
- Precise Gamma Scan
- GASR (if not failed)
- Optical Microscopy
- SEM
- EPMA
- LFA
- BU

Conclusions from Completed Pre-Transient Analysis

- Confirmation of test and sibling pin suitability:
  - No visual corrosion from storage
  - No uncharacteristic features
- Established baseline steady-state behavior
  - Axial elongation within range of reported values for U-19Pu-10Zr and U-10Zr
  - Diametral strain within range of reported values for HT9 clad metallic fuel pins
  - Cs-137 distribution consistent with expected results for Na-bonded pins
  - Steady-state fuel structure evolution analyzed through DE

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